Theoretical Analysis of FWM by ISBT in InGaAs/AlAsSb QWs for Wavelength Conversion

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Abstract—**The mechanism of FWM (four-wave mixing) by ISBT (inter-sub-band transition) in InGaAs/AlAsSb QWs (quantum wells) is analyzed theoretically. The estimated values of the third order nonlinear optical susceptibility are sufficient for coherent wavelength conversion.**

Keywords-four wave mixing; wavelength conversion; inter sub-band transition

I. INTRODUCTION

In the next generation optical network systems, wavelength conversion is expected to play an important role [1]. Recent progress of phase modulation formats or multi-level modulation formats needs coherent wavelength conversion, by which not only amplitude information but also phase information of signals can be converted.

FWM in active semiconductor waveguides is a promising method to realize the coherent wavelength conversion because of their high conversion efficiency with short interaction length, which enables no consideration of the phase match condition [2]. The shortcoming of FWM using active waveguides such as LDs or SOAs is signal degradation by the addition of ASE (amplified spontaneous emission) noise. FWM in passive waveguides is required. The efficiencies using passive semiconductor waveguides, however, are not sufficient for wavelength conversion.

Materials with high optical nonlinearity are effective for the increase of conversion efficiency. InGaAs/AlAsSb quantum wells (QWs) a promising candidate because of their responsibility of inter sub-band transition (ISBT) for 1.5μm wavelength light using optical communication systems, ultra-fast response of few-ps, and high optical nonlinearity [3]. In addition, InGaAs/AlAsSb QWs have monolithic integration capability with other InP-based optical devices. The utilization of phase-modulation for TE-polarization waves by ISBT absorption of TM-polarization waves creates new applications of InGaAs/AlAsSb ISBT optical waveguides. Excellent results such as optical de-multiplex 160Gbps to 10Gbps [3] are demonstrated by using InGaAs/AlAsSb ISBT optical waveguides. In addition to the wavelength conversion of ultra fast signals of 160Gbps [4], the possibility of wavelength conversion with FWM has been demonstrated [5]. In spite that high FWM efficiencies are expected, the mechanism of FWM has not been well investigated.

In this work, we discuss the FWM mechanism in InGaAs/AlAsSb ISBT QWs. Two kinds of mechanism are discussed. One is due to the nonlinear response of optical dipoles in the bands and estimated by the density matrix formulas. The other is that due to the phase modulation by the real excitation of ISBT and estimated by phenomenological approach.

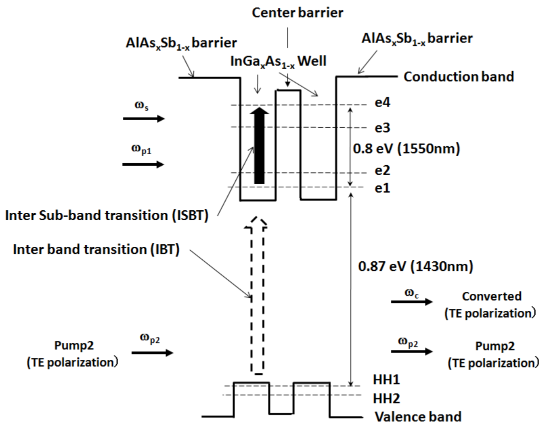

Fig. 1. Band diagram of $In_xGa_{1-x}As/AlAs_xSb_{1-x}$ double quantum well and four interacting waves in the quantum well.

II. THE MECHANISM OF FWM IN ALASSB/INGAAS QWS

Figure 1 shows the band diagram of InGaAs/AlAsSb DQWs (Double Quantum Wells). Main difference from other QWs such as /InGaAsP on InP substrates is that the band offset of the conduction band is larger than 1eV. ISBT energy can be set to 0.8 eV corresponding to the optical communication wavelength range of 1.55 μm with TM polarization. On the other hand, the band gap energy is slightly larger than 0.8 eV. Inter band transition (IBT) energy is set so that the QWs is transparent for lights with the wavelength of 1.55 μm and TE polarization. The InGaAs/AlAsSb QWs consists in a quasi-three level system for the light of 1.55 μm wavelength range. The case is considered that a signal with TM polarization and angular frequency ω_s, a pump with TM and ω_{p1}, and another pump with TE and ω_{p1}, are put into the QWs and generate a converted wave with TE and ω_c.

We described the linear and nonlinear optical responses by the density matrix formulas under the relaxation time constant approximation [6]. The description of the third order nonlinear optical susceptibilities consists of 48 terms [6]. Considering the resonant condition and that Fermi-level is set to the bottom of the conduction band, only two terms have significant values.

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One means the process that two photons are absorbed by IBT and IBST and two photons are emitted. The other expresses the process that a photon is absorbed by IBT and then the absorption of a photon and the emission of two photons are caused by the second order of nonlinear optical dipole due to the first photon absorption. Both processes are instantaneous process and give same $\chi^{(3)}$ values.

Another third order optical nonlinearity is caused by the real excitation of the ISBT. This excitation of inter sub-band modifies the dispersion curve determined by the IBT, and changes the refractive index for TE-polarization waves. When two TM-polarization waves of a pump and a signal are absorbed by the ISBT, the beating of two waves causes the pulsation of the carrier distribution in the conduction band, and modulates another probe wave of TE-polarization, which resulting in the generation of the replica wave of the same phase rotation with the signal and the conjugate wave of the opposite phase rotation. Similar to the carrier density pulsation effect in LDs or SOAs, this real excitation mechanism is described by a classical rate equation [2].

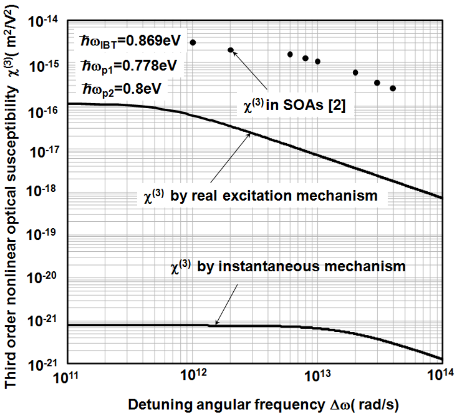

Fig. 2. The dependence of $\chi^{(3)}$ on detuning between ω_s and ω_{p1} in InGaAs/AlAsSb quantum wells.

III. THE RESULTS

The estimations of the third order nonlinear susceptibilities $\chi^{(3)}$ using above two mechanisms are shown in Figure 2. The dependence of the $\chi^{(3)}$ on detuning between ω_s and ω_{p1} is shown. The band width of $\chi^{(3)}$ by the real excitation mechanism is limited by the relaxation time of ISBT. The values decrease as the detuning between ω_s and ω_{p1} increases. On the other hand, the value of $\chi^{(3)}$ by the instantaneous mechanism is flat in the range of less than 10^{13} rad/s. The band width is limited by the relaxation time of electron states in the conduction band. The values of $\chi^{(3)}$ by the real excitation mechanism are five order of magnitude larger than the values of $\chi^{(3)}$ by the instantaneous mechanism. This is due to that refractive index change due to the ISBT excitation causes due to not only the change of carrier number in the bottom of the conduction band, but also the temperature change of carriers [7]. For comparison, the values of active region in SOAs [2] are also plotted by dots in Figure 2. The $\chi^{(3)}$'s in InGaAs/AlAsSb QWs are one order of magnitude smaller than those of active region in SOAs. In the case of SOAs, all interacting photons completely resonate with the band gap energy. On the other hand, only ω_s and ω_{p1} resonate with the ISBT energy, but ω_c and ω_{p2} off-resonate slightly from the IBT energy for avoiding the inter-band absorption in the case of InGaAs/AlAsSb QWs.

The dependence of $\chi^{(3)}$ on detuning between the converted signal energy and the band-gap energy $\hbar(\omega_c - \omega_{IBT})$ is shown in figure 3. The $\chi^{(3)}$ increases when $\hbar\omega_c$ approaches band-gap energy. As the resonance factor contributes to the increase of the $\chi^{(3)}$, the increase factor of $\chi^{(3)}$ by the instantaneous mechanism is twice of those of $\chi^{(3)}$ by the real excitation mechanism. Nevertheless, the $\chi^{(3)}$ by the real excitation mechanism is dominant as the FWM process in the wavelength range of 1.4 to 1.6 μm. The experimental results shown by dots in Figure 3 agree with the calculated results of the $\chi^{(3)}$by the real excitation mechanism.

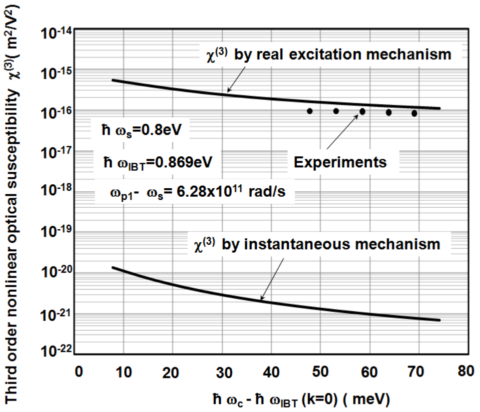

Fig. 3. The dependence of $\chi^{(3)}$ of the detuning between the converted signal energy and the band-gap energy.

IV. CONCLUSION

The estimated values of $\chi^{(3)}$ are sufficient for wavelength conversion. When we use pump powers of 20 dBm, an input signal power of 10 dBm, and InGaAs/AlAsSb QWs with the band gap energy of 0.85 eV, the converted signal of -30 dBm will be obtained by a waveguide with a length of 250 μm. Considering that there is no additional ASE noise differently from the case of SOAs, sufficient signal to noise ratio will be obtained.

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